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Can CP entanglement with the environment mask CP violation?

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Abstract

We consider departures from hamiltonian dynamics in the evolution of neutral kaons due to their interactions with the environment that generate entanglement among them.

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1 Introduction

CP violation was first measured in [1] long ago, in the mixing of the neutral kaons, the so called *indirect* CP violation, whereas it was not until recently that *direct* violation, in the decay amplitudes to two pions, was experimentally established (see [2] and references therein). There are at present a few dedicated experiments in project to make precision measurements of the CP breaking parameters. The analysis of their data may require to take properly into account the effects of *decoherence* due to entanglement of the neutral kaon system with the environment in which it evolves, which entails a pure kaon state to evolve into a mixed one. We consider the evolution of neutral kaons in the presence of matter, in an environment that is not the perfect vacuum, which generates departures from hamiltonian dynamics in the kaon sub-system. These are effects that exist in addition to the weak interactions and are dominated by the strong interactions of the kaons and the environment: they lead to an effective breaking of charge conjugation, because the environment is made of matter, not of anti-matter; and to an effective breaking of time-reversal invariance associated to the large number of degrees of freedom in the environment that leads to irreversibility.

Similar analysis can be found in the literature [3], [4], [5]. There, the motivation is to study decoherence effects that come from quantum gravity. Ours is the interaction with the environment that is not the vacuum.

The neutral kaon evolution in the vacuum is analyzed with the Schrödinger equation

$$i\dot{\rho}(t) = H\rho(t) - \rho(t)H^\dagger, \quad (1)$$

where H is the LOY [6] effective hamiltonian $H = \sum_{I=S,L} \lambda_I |K\rangle \langle \tilde{K}_I|$, which is not hermitean and its eigenstates $\lambda_I = m_I - \frac{i}{2}\gamma_I$ possess a non-vanishing imaginary part of their decay rates. S, L stand for the *short* and *long* components, and $|\tilde{K}_I\rangle$ are such that $\langle \tilde{K}_I | K_J \rangle = \delta_{IJ}$. Recall that $m_S \simeq m_L \simeq 500 \text{ MeV}$, $\Delta m = m_L - m_S = 3.5 \times 10^{-12} \text{ MeV}$, $\gamma_S = 7.3 \times 10^{-12} \text{ MeV}$ and $\gamma_L = 1.3 \times 10^{-14} \text{ MeV}$.

The $|K_I\rangle$ have diagonal evolution $|K_I(t)\rangle = e^{-i\lambda_I t} |K_I(0)\rangle$. In terms of the CP eigenstates

$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon_S|^2}} (|K_1\rangle + \epsilon_S |K_2\rangle), \quad |K_L\rangle = \frac{1}{\sqrt{1+|\epsilon_L|^2}} (|K_2\rangle + \epsilon_L |K_1\rangle); \quad (2)$$

they reduce to $|K_1\rangle, |K_2\rangle$, respectively, i.e., to the CP eigenstates $\frac{1}{2}(|K^0\rangle \pm |\bar{K}^0\rangle)$ if CP is conserved.

At this point we recall that CPT conservation requires $\epsilon_S = \epsilon_L$; T invariance, $\epsilon_S + \epsilon_L = 0$; and CP, $\epsilon_S = \epsilon_L = 0$.

Indirect CP violation has been measured

$$\epsilon \simeq 2.3 \times 10^{-3} e^{i\pi/4}, \quad (3)$$

(CPT conservation is assumed, $\epsilon_S = \epsilon_L \equiv \epsilon$.) Direct CP violation has also been measured

$$\epsilon'/\epsilon \sim 2 \times 10^{-3}, \quad (4)$$

where

$$\frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)} \equiv \epsilon + \epsilon', \quad \frac{A(K_L \rightarrow \pi^0 \pi^0)}{A(K_S \rightarrow \pi^0 \pi^0)} \equiv \epsilon - 2\epsilon'.$$

2 Interaction with the environment

The evolution of the *total* system [Kaon + (Large) Environment] is unitary, with the time evolution operator given by $U(t) = \exp(-iH_{Total}t)$; whereas the dynamics of the kaon subsystem alone is obtained by tracing out the environment degrees of freedom:

$$\rho_K(t) = Tr_{ENV} \left(U(t) \rho_{K+ENV}(0) U^\dagger(t) \right). \quad (5)$$

This gives a complicated evolution for ρ_K , even if the initial conditions are a direct product $\rho_{K+ENV}(0) = \rho_K(0) \otimes \rho_{ENV}(0)$. However, when the interaction is tiny (e.g., as in the case of a diluted environment) the dynamics of ρ_K becomes approximately free from memory effects (Markovian), and it is dictated by a Lindblad master equation of the form

$$\dot{\rho} = -i \left(H_{eff} \rho(t) - \rho(t) H_{eff}^\dagger \right) + \sum_n \left(A_n \rho A_n^\dagger - \frac{1}{2} \rho A_n^\dagger A_n - \frac{1}{2} A_n^\dagger A_n \rho \right), \quad (6)$$

(henceforth ρ stands for ρ_K). Memory effects are being neglected. Notice that the new piece is linear in ρ but *quadratic* in the unspecified operators A_n : the Lindblad equation encodes a new dynamics that is not purely hamiltonian. The new term entails decoherence, it makes pure states evolve into mixed states. Since the opposite process does not occur, i.e, no mixed state evolves to a pure one, we demand that the von Neumann entropy $-\rho \log \rho$ should not increase, under evolution with the new piece only.

The operators A_n are governed by the strong interactions and the properties of the medium. Since strong interactions conserve strangeness, which in the absence of the weak interactions would become a superselection quantum number, we further demand that *any* density matrix, at large times, should end up as a mixture of $|K^0\rangle$ and $|\bar{K}^0\rangle$.

The most general parametrization that satisfies the above considerations leads, for the two state neutral kaon system, to a non-hamiltonian contribution in (6)

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & s_1 & 0 & 0 \\ 0 & 0 & s_{22} & s_{23} \\ 0 & 0 & s_{23} & s_{33} \end{pmatrix} \begin{pmatrix} \rho^0 \\ \rho^1 \\ \rho^2 \\ \rho^3 \end{pmatrix}. \quad (7)$$

where in the CP eigenbasis $\rho \equiv \frac{1}{2}(\rho^0 I + \vec{\rho} \cdot \vec{\sigma})$.

The matrix s_{ij} is *symmetric*, $s_1, s_{22}, s_{33} > 0$, it has positive eigenvalues the smallest of which is s_1 . They also verify the relations [3]

$$\begin{aligned} s_1 &\leq s_{22} + s_{33}, & s_{33}^2 &\geq (s_1 - s_{22})^2, \\ s_{22} &\leq s_1 + s_{33}, & s_{22}^2 &\geq (s_1 - s_{33})^2, \\ s_{33} &\leq s_1 + s_{22}, & s_1^2 &\geq (s_{22} - s_{33})^2. \end{aligned}$$

The hamiltonian part gets a contribution H_l that is of the order $o(s_{ij})$.

For example, in an environment of infinitely heavy particles which act as scattering centers, since no entanglement is generated $s_{ij} = 0$ and H_l adopts the Kabir-Good form

$$(H_l)_{Kabir-Good} = \frac{2\pi n}{m_K} \left(f_{K^0}(0) |K^0\rangle \langle K^0| + f_{\bar{K}^0}(0) |\bar{K}^0\rangle \langle \bar{K}^0| \right); \quad (8)$$

$f(0)$ is the forward scattering amplitude of the kaon with one center and n stands for the density of scatterers.

3 Estimates

Can these effects be detected? How large do we expect them be? In order to work out the time evolution of the density matrix from equation (6) we assume $\frac{s_{ij}}{\Delta m}$ of the order of the smallest observed effect $\epsilon' \sim 10^{-6}$. With the hierarchy

$$\gamma_L/\gamma_S, \epsilon \sim 10^{-3} \gg \delta_K, \frac{s_{ij}}{\Delta m}, \epsilon', \epsilon^2 \sim 10^{-6},$$

we calculate the evolution up to $o(\frac{s_{ij}}{\Delta m})$. Here, $\delta_K = \frac{\epsilon_L - \epsilon_S}{2}|_{eff}$ amounts to effective CPT breaking, coming from the hamiltonian part of the new piece in (reflindblad). On dimensional grounds we take $s \sim \sigma n$, and $\frac{s}{\Delta m} \sim \frac{\sigma n}{\Delta m} \sim o(\epsilon') \sim 10^{-6}$ can be achieved with $n \sim 10^{20}/cm^3 \sim [N_{Avogadro}/cm^3]/1000$, where $\sigma \sim 1 fm^2$.

In the basis $|K_S\rangle, |K_L\rangle$ the hamiltonian part of the evolution is straightforwardly obtained, to all orders in ϵ_S, ϵ_L , if needed. With the notation

$$\bar{\gamma}_L = \gamma_L + \frac{s_{33}}{2}, \quad \bar{\gamma}_S = \gamma_S + \frac{s_{33}}{2}, \quad \gamma = \gamma_S + \gamma_L + s_1 + s_{22};$$

$$x_{33} = \frac{s_{33}}{2\gamma_S}, \quad x_{23} = \frac{s_{23}}{2|\Delta\lambda|}, \quad x = \frac{s_{22} - s_1}{2\Delta m}, \quad \phi = \text{Arg}\Delta\lambda.$$

.

$$\Delta\lambda \equiv \lambda_L - \lambda_S = (m_L - m_S) + \frac{i}{2}(\gamma_S - \gamma_L),$$

the time evolution of an initial $|K^0\rangle$ reads, to first order in perturbation theory,

$$\begin{aligned} \rho_{SS}(t) &= \frac{x_{33}}{2} e^{-\bar{\gamma}_L t} - x_{23} \cos(\Delta m t + \phi) e^{-\frac{1}{2}\gamma t} + \left(\frac{1}{2} - \text{Re}\epsilon_L + 2(\text{Re}\epsilon)^2 - \frac{x_{33}}{2} + x_{23} \cos \phi \right) e^{-\bar{\gamma}_S t} \\ \rho_{LL}(t) &= \left(\frac{1}{2} - \text{Re}\epsilon_S + 2(\text{Re}\epsilon)^2 + \frac{x_{33}}{2} - x_{23} \cos \phi \right) e^{-\bar{\gamma}_L t} + x_{23} \cos(\Delta m t - \phi) e^{-\frac{1}{2}\gamma t} - \frac{x_{33}}{2} e^{-\bar{\gamma}_S t} \\ \rho_{SL}(t) &= \frac{x_{23}}{2} e^{-i\phi} e^{-\bar{\gamma}_L t} + \left[\left(\frac{1 - (\epsilon_S^* + \epsilon_L) + 4(\text{Re}\epsilon)^2}{2} + i x_{23} \sin \phi \right) e^{i\Delta m t} + \frac{x}{2} \sin(\Delta m t) \right] e^{-\frac{1}{2}\gamma t} \\ &\quad - \frac{x_{23}}{2} e^{i\phi} e^{-\bar{\gamma}_S t} \end{aligned} \quad (9)$$

and similarly for the $|\bar{K}^0\rangle$.

4 How can the new effects be uncovered?

The new effects cannot be completely absorbed by redefinitions of the parameters in the effective hamiltonian. Except for ϵ'/ϵ , in all the other CP violating asymmetries that have been measured so far associated with the decays into 2π and semileptonic into $\pi^\pm l\nu$, they give subleading contributions and are thus expected to bear little influence in the analysis.

Furthermore, in the experiments that have been performed, all the measured observables correspond either to detection of decay rates at large times, when only the K_L component survives, or to integrated rates. The exception is CPLEAR where the time evolution can be traced in the interval $\tau_S < t < 20\tau_S$. We find that a better determined time evolution could help in measuring the new parameters of the experiment. It is also found that it is rather the symmetric combinations of rates that single out the new coefficients. For example, at large times

$$P(K^0 \rightarrow \pi\pi; t) \stackrel{\gamma_{st} \gg 1}{\simeq} \frac{1}{2}(x_{33} + |\epsilon|^2)e^{-\gamma_L t},$$

with an independent measure of ϵ the parameter $x_{33} = \frac{s_{33}}{2\gamma_S}$ could be determined -the normalization can be obtained from small t. It also appears as subleading in

$$P(K^0 \rightarrow \bar{K}^0) + P(\bar{K}^0 \rightarrow K^0) \stackrel{\gamma_{st} \gg 1}{\simeq} \left(\frac{1}{2} + 4(Re\epsilon)^2 + x_{33} \right) e^{-\gamma_L t},$$

from which only an extremely precise experiment could determine it.

Furthermore, mathematically, at short times

$$P(K^0 \rightarrow \bar{K}^0) \sim P(\bar{K}^0 \rightarrow K^0) \stackrel{\gamma_{st} \ll 1}{\sim} \frac{1}{2}s_1 t.$$

5 ϵ'/ϵ in two-pion decays

Recently the double ratio

$$\frac{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^0\pi^0)/\Gamma(K_S \rightarrow \pi^0\pi^0)}$$

has been measured. In a perfect vacuum this is

$$\frac{|\epsilon + \epsilon'|^2}{|\epsilon - 2\epsilon'|^2} \sim 1 + 6Re\left(\frac{\epsilon'}{\epsilon}\right).$$

However, in matter the result is

$$1 + 6Re\left(\frac{\epsilon'}{\epsilon_L}\right) \frac{|\epsilon_L|^2}{|\epsilon_L|^2 + x_{33}}.$$

Since x_{33} is positive, the effect of entanglement with the environment would decrease the signal, i.e., it would be bigger than measured. Here ϵ_L comes from the hamiltonian part of the evolution.

We believe that a measurement of these parameters in each experiment of precision would be interesting on its own, in addition to being necessary for properly subtract them. In this way one would uncover the effects of entanglement with the environment of the neutral kaons, that certainly, unavoidably exist.

6 Conclusions

We draw the attention to effects of interaction with the environment in neutral kaon evolution, that maybe of relevance in the analysis of the CP breaking parameters, made from more complete and precise data that will be available soon, in the future (e.g., KLOE in Eurodaphne). The Lindblad master equation provides a *universal* form that incorporates the tiny corrections of non-hamiltonian evolution. The effects are expected to be more important in B physics for although the B's decay faster than the kaons, their entanglement with the environment will be more efficient, given the B meson mass of about 5 GeV , a factor of ten larger than that of kaons.

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